

New limits on bosonic dark matter, solar axions, Pauli Exclusion Principle violation, and electron decay from the low-energy spectrum of the MAJORANA DEMONSTRATOR

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The existence of cosmic dark matter (DM) is well established but its exact nature has yet to be determined. Stringent limits on weakly interacting massive particle (WIMP) DM candidates motivate alternative models. We present results for searches of keV-scale pseudoscalar and vector dark matter using 478 kg d of commissioning data from the MAJORANA DEMONSTRATOR (MJD), a Ge-based neutrinoless double-beta decay experiment operating in the Sanford Underground Research Facility. We did not detect a positive dark matter signal, and a 90% upper confidence interval on the electron DM coupling was estimated. Our most stringent limit on DM coupling was set for axion-like particles of mass 11.8 keV with $g_{Ae} < 4.5 \times 10^{-13}$, and $\frac{\alpha'}{\alpha} < 9.7 \times 10^{-28}$ for vector DM. We also report limits from additional rare-event searches, including 14.4 keV solar axions and Pauli Exclusion Principle violating electron transitions. An upper limit of $g_{AN}^{eff} \times g_{Ae} < 3.8 \times 10^{-17}$ was found for the solar axion coupling; a limit on the strength of a non-Paulian transition in Ge of $\frac{1}{2}\beta^2 < 8.5 \times 10^{-48}$ was set, and a limit of $\tau_e > 1.2 \times 10^{24}$ y for $e^- \rightarrow \nu\bar{\nu}\nu$ was found at the 90% confidence level.

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Although, weakly interacting massive particles (WIMPs) with masses in the GeV to TeV range are well-motivated candidates for cold dark matter (CDM) [1, 2], numerous experiments have not directly detected them,

resulting in very restrictive exclusion limits [3–5]. CDM can account for the observed large scale structure of the universe, but has difficulties on sub-galactic scales, leading to an interest in keV-scale dark matter models [6–8].

Furthermore, the lack of direct detection of WIMPs or related particles at the Large Hadron Collider and by direct detection experiments have led to consideration of alternative models. See [9] and references therein for an extensive review of these models and their motivation.

DM candidates with mass at the keV-scale must have a high number density to compensate for their low mass and a correspondingly small, or super-weak, interaction cross section to explain why they have not yet been detected. Their small mass and low energy make them difficult to detect via elastic nuclear scattering [10], incurring significant challenges in searches for fermionic candidates such as the sterile neutrino or the gravitino. However, interactions in which the particle is absorbed and its rest-mass energy is passed to atoms or nuclei in the detector may render them observable [7, 11, 12] by producing a peak in the detector energy spectrum.

In this paper, we present new limits for pseudoscalar (i.e. axion-like) and vector DM electronic coupling from data taken during a 2015 commissioning run of the MAJORANA DEMONSTRATOR (MJD). We also report limits from three additional rare event searches which would also result in a mono-energetic peak in our data: the coupling of 14.4 keV solar axions that might be emitted in the M1 transition of solar ^{57}Fe nuclei, Pauli Exclusion Principle violating (PEPv) electronic transitions, and the electron decay mode, $e^- \rightarrow 3\nu$.

The DEMONSTRATOR, described in detail in Ref. [13], is a neutrinoless double-beta decay ($0\nu\beta\beta$) experiment located 4850 ft underground at the Sanford Underground Research Facility in Lead, SD [14]. MJD consists of two separate custom ultra-low background modules, each containing 7 arrays of P-type point contact (PPC) high-purity germanium (HPGe) detectors with a total mass of 44.1 kg, of which 29.7 kg is enriched to 88% ^{76}Ge . The geometry of the PPC detectors results in low capacitance, reduced electronic noise, and permits good energy resolution with very low energy thresholds. In addition, PPC Ge detectors have advantageous pulse-shape discrimination capabilities [15–17]. Previous experiments have exploited these capabilities to perform high-sensitivity searches for light WIMP and bosonic DM [18–20] as well as neutrinoless double-beta decay searches [21].

The MJD modules are surrounded by a copper shield, a lead shield, an active muon veto [22], and a polyethylene neutron shield. Within the shielding, radon is purged via liquid nitrogen boil-off. The inner 5 cm of the copper shield, the cryostats which house the detectors, and the crystal support structures are made from copper electroformed in an underground facility. MJD relies on careful material selection and handling [23] to reduce intrinsic and extrinsic radioactive background, making it well-suited for dark matter and other rare-event searches.

Signals from the PPC detectors are amplified and shaped by a custom low-noise resistive-feedback pre-amplifier with a measured equivalent noise charge (ENC)

of ~ 85 eV in Ge-detector-equivalent FWHM resolution [24]. The amplifier provides low-gain and high-gain outputs which are digitized separately by a custom 14-bit 100 MHz VME-based digitizer designed for the GREYTA experiment [25]. Signals are digitized continuously and triggers are generated when the output of a firmware-based trapezoidal filter trigger exceeds the pre-set threshold for that channel. An internal pulser (~ 0.1 Hz), implemented by injecting charge through capacitive coupling to the gate of the preamplifier’s front-end JFET, is used to monitor detector live time and gain stability. The data-acquisition system is controlled and monitored by the ORCA software package [26]. Data from the muon-veto system is not utilized in this analysis.

The data used in this paper were acquired during the commissioning of the first module (Module 1) from June 30 to Sept. 22, 2015. The innermost 5 cm of electroformed copper shielding was not yet installed and the exterior neutron shield was incomplete. Module 1 contains 20 enriched Ge detectors and 9 natural-Ge detectors manufactured by ORTEC [27] and Canberra [28], respectively. The natural detectors produced using standard techniques have a relatively high background due to cosmogenic activation products and are only used for systematic studies in the results presented here. The enriched detectors used in the bosonic dark matter analysis have significantly lower amounts of cosmogenic activation due to care taken in minimizing cosmic ray exposure during manufacturing and transport (see Fig. 1). Seven enriched detectors were unavailable for this analysis due to failed electrical connections or high noise rates. The active mass of the remaining 13 detectors was computed using detector dead layer measurements provided by ORTEC, which were verified via collimated ^{133}Ba source scans. The total active enriched mass was 10.06 ± 0.13 kg. The live-time was 47.503 ± 0.001 d, resulting in an exposure of 478 ± 6 kg d.

Transient and other irregular noise pulses contaminate the spectrum between 2 – 70 keV. Most of the non-physical waveforms are due to accidental re-triggering during baseline restoration after pulser events. These are easily removed by eliminating events with more than one detector hit or by using pulse-shape discrimination. The acceptance of these cuts is 99.98% with negligible uncertainty.

Slow pulse waveforms with rise-times of ~ 1 μs or longer constitute a significant background below 30 keV, as recognized by previous experiments [18–20, 29]. Slow pulses are energy-degraded events that originate in low-field regions of the detector near the surface dead layer, where diffusion is the dominant mode of charge transport. At energies < 10 keV, discriminating slow pulses using pulse rise-time measurements becomes increasingly difficult due to the worsening signal to noise ratio. A more robust parameter, T/E , was developed. A triangle filter

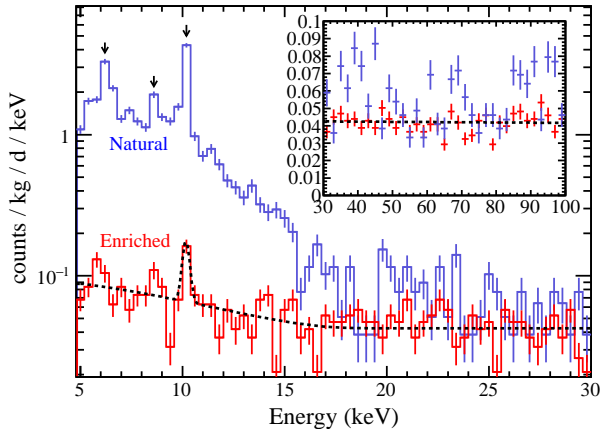


FIG. 1. (Color online) Energy spectra from 195 kg d of natural (blue) and 478 kg d of enriched (red) detector data. A fit of the background model (linear + tritium beta spectrum + ^{68}Ge K-shell) to the enriched spectrum is also shown (dotted black). The background rate and slope, along with the tritium and K-shell rate were floated in the fit. The background fit χ^2/NDF is 75.7/85. Cosmogenic isotopes in the natural detectors produce peaks at 10.36 keV (^{68}Ge), 8.9 keV (^{65}Zn), and 6.5 keV (^{55}Fe) on top of a tritium beta decay continuum. The FWHM of the 10.4 keV peak is ~ 0.25 keV. The spectrum shown does not include a T/E cut acceptance correction.

with a 100 ns ramp time and a 10 ns flat-top time was applied to each waveform, and the maximum (T) value of the result was measured. The T -value was normalized by an energy parameter, (E), which was reconstructed offline by finding the maximum [30] of a trapezoidal filtered waveform with a filter rise time of $4\ \mu\text{s}$ and flat-top time of $2.5\ \mu\text{s}$. This parameter exhibited good separation between fast and slow-pulse waveforms down to ~ 3 keV, well below the analysis threshold.

The signal acceptance of the T/E cut was measured by capacitively injecting simulated signal pulses of varying amplitude directly onto the detector's outer contact using a precision waveform generator. The energy dependent acceptance was determined by finding the fraction of these events that pass the cut at set pulse amplitudes. An error function was fit to the acceptance fractions to estimate the acceptance between pulser peak events. Only 3 of the 13 detectors used in this analysis were instrumented with the required electronics to perform this test and the smallest-valued (most conservative) acceptance function, ranging from 96% at 5 keV to 100% at 20 keV, was applied in the DM rate analysis, Eq 3. The detector acceptance functions varied by at most 1%. The energy dependent acceptance uncertainty was determined from the error function fit: $\eta(E) = \text{Erf}(E - \mu)/(\sqrt{2}\sigma)$. The fit values were $\mu = -26 \pm 4$ keV and $\sigma = 13.7 \pm 1.7$ keV with a strong anti-correlation, $\text{corr}(\mu, \sigma) \sim -1$.

A ^{228}Th line source inserted into a helical calibration

track surrounding the cryostat was used for energy calibration. Multiple calibration periods were interspersed between background data collection to track and account for long-term drift in gain. Statistically significant peaks in the ^{228}Th decay chain energy spectrum were used to calibrate the energy spectra of each detector independently. The wall of the cryostat and the dead layer of the crystals efficiently attenuated the lowest energy gamma and x-rays from the calibration source. In a given calibration period, the individual detector exposure was not large enough to measure any statistically significant peaks below the 238.6 keV ^{210}Pb line. To extend our calibration to lower energies, we included the measured baseline noise as the zero point energy in the fit.

We combined the calibration spectra from the 13 detectors, and summed a total of 102.8 hours of calibration data over all of the calibration periods. The resulting high statistics spectrum permitted peaks from Bi X-rays and Th and Pb gamma rays to be used to help quantify the uncertainty in the energy scale at lower energies. A small systematic offset in the energy-scale (E_S) of ~ 0.2 keV from known peak energies was observed at lower energies. The offset is consistent with residual digitizer nonlinearity effects, which were estimated by comparing energy measurements from low-gain and high-gain channels. A linear correction (ΔE):

$$\Delta E(E_S) = \alpha_E(E_S - 95.0\text{ keV}) + E_0, \quad (1)$$

was applied to mitigate the offset. The parameters $\alpha_E = -0.0014 \pm 0.0008$ and $E_0 = -0.256 \pm 0.016$ keV were determined by fitting a line to the peak-centroid offset values of the low-statistics peaks between 70 and 120 keV. The correlation coefficient was $\text{corr}(\alpha_E, E_0) = -0.22$. The correction was then extrapolated to lower energies. As a check, the predicted offset at 10.36 keV, the ^{68}Ge cosmogenic K-shell cascade peak, was computed and found to be -0.12 ± 0.07 keV. This peak in the natural detectors was measured at 10.22 keV, which is consistent with the correction model prediction in Eq. 1 to within the parameter uncertainties. We are improving our non-linearity correction and expect to remove this offset in future analyses.

A multi-peak fitting routine was applied to the summed calibration spectrum to determine the energy-dependent widths (σ) of peaks in the ^{228}Th spectrum in the energy range 0-260 keV, where the $E=0$ value is taken from the energy width of forced-acquisition waveforms. The widths were fit to:

$$\sigma_E(E) = \sqrt{\sigma_0^2 + \langle \varepsilon \rangle F E}, \quad (2)$$

and the resulting fit values are $\sigma_0 = 0.16 \pm 0.04$ keV and $F = 0.11 \pm 0.02$. The fit parameters were fully correlated, $\text{corr}(\sigma_0, F) \sim 1$. The constant $\langle \varepsilon \rangle = 2.96$ eV, is the average energy required to produce an electron-hole pair in Ge.

Limits on pseudoscalar dark matter axio-electric coupling were calculated similarly to [31]. For comparison with other experiments, we set the Milky Way halo density to $\rho_{DM} = 0.3 \text{ GeV cm}^{-3}$ [32] and assumed that pseudoscalar DM constitutes the total density. The expected number of detected counts, dN/dE at energy E , assuming a pseudoscalar mass of m_A in keV, is given by [31, 33],

$$\frac{dN}{dE}(E; m_A) = \Phi_{DM}(m_A) \sigma_{Ae}(m_A) \eta(E) \frac{1}{\sqrt{2\pi}\sigma_E(m_A)} \exp\left(-\frac{(E - m_A)^2}{2\sigma_E^2(m_A)}\right) MT, \quad (3)$$

$$\Phi_{DM} = \rho_{DM} \frac{v_A}{m_A} = 7.8 \times 10^{-4} \left(\frac{1}{m_A}\right) \cdot \beta \text{ [/barn/day]}, \quad (4)$$

$$\sigma_{Ae}(m_A) = \sigma_{pe}(m_A) \frac{g_{Ae}^2}{\beta} \frac{3m_A^2}{16\pi\alpha m_e^2} \left(1 - \frac{\beta^2}{3}\right). \quad (5)$$

where $\beta = v_A/c$ is the average DM velocity with respect to the earth, Φ_{DM} is the average DM flux at Earth, σ_{Ae} is the axio-electric cross section as a function of energy, σ_E is the energy resolution at $E = m_A$, given by Eq. 2, MT is the exposure of the detectors used in this analysis, and $\eta(E)$ is the T/E cut acceptance function. In Eq. 5, σ_{pe} is the photoelectric cross section in Ge [34]. In this analysis, the peak energy of interest is the pseudoscalar mass (m_A). We take $\beta = 0.001$ [31, 35], roughly the mean of the dark matter velocity distribution with respect to the Earth.

We place an upper limit on the pseudoscalar dark matter coupling constant g_{Ae} using an unbinned profile likelihood method [36–38]. The likelihood function incorporates a DM signal PDF, modeled with Eq. 3, a linear background, the tritium spectrum and a 10.36 keV cosmogenic x-ray peak. A multi-dimensional Gaussian penalty term floats the nuisance parameters (α_E , E_0 , σ_E , and η) in the likelihood function according to their covariance matrices. The best fit to the background model is shown in Fig. 1.

A comparison of our limit on the coupling constant, g_{Ae} to previous results is shown in Fig. 2. For values of m_A between 20 and 100 keV, our limits are an improvement over EDELWEISS [31], whereas XMASS [39] has the best limit above 40 keV. We set leading limits for $m_A < 15$ keV due to lower cosmogenic activation in our detectors.

Using the same data and analysis, we also set limits on the electronic coupling of vector bosonic DM [11]. The interaction rate for vector DM is:

$$\Phi_{DM}(m_V) \sigma_{Ve}(m_V) = \frac{4 \times 10^{23}}{m_V} \left(\frac{\alpha'}{\alpha}\right) \frac{\sigma_{pe}(m_V)}{A} \text{ [/kg/d]}, \quad (6)$$

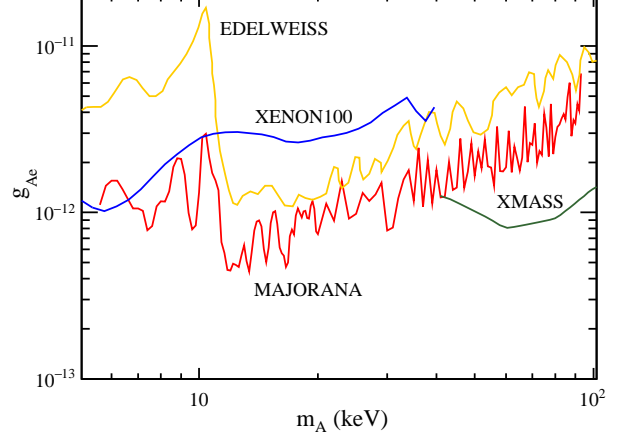


FIG. 2. (Color online) The 90% UL on the pseudoscalar axion-like particle dark matter coupling from the MAJORANA DEMONSTRATOR (red) compared to EDELWEISS [31] (orange), XMASS [39] (green), and XENON [35] (blue). Recent results by LUX have not yet been published [40], and new results from CDEX [41] are available on the arXiv [41].

where A is the atomic mass of Ge, m_V is the vector boson mass in keV, and α' is the coupling of vector DM to electrons, analogous to the electromagnetic fine structure constant, α . The expected number of detector counts at energy E is found by replacing the axio-electric interaction rate in Eq. 3 with the vector-electric rate, with m_V substituted for m_A . Limits on the vector coupling from the same unbinned likelihood analysis described above are shown in Fig. 3. In the case of vector DM, the experimental constraints are more stringent than astrophysical limits, excepting red giant (RG) stars.

In addition to generic pseudoscalar and vector DM, we analyzed our sensitivity to solar axions. ^{57}Fe has a large solar abundance and its first excited state at 14.4 keV is thermally excited within the Sun's interior. Axion emission is possible from the decay of this state [44]. Electric coupling of these axions to atomic electrons in the detector would manifest as a peak at 14.4 keV. No such peak was observed in MJD, and a limit on the product of the effective axio-nuclear coupling, g_{AN}^{eff} , of solar axions (see [45]) and the axio-electric coupling, g_{Ae} , was determined. Replacing the flux in Eq. 4 with [31]

$$\Phi_{14.4} = \beta^3 \times 4.56 \times 10^{23} (g_{AN}^{eff})^2 \text{ [/cm}^2\text{/s]}, \quad (7)$$

and substituting m_A in Eq. 3 with 14.4 keV, we use the unbinned likelihood analysis to determine a limit on the coupling constant. Since this is a mono-energetic transition, the reduced axion velocity, β , depends on the mass of the axion, which can range from zero to 14.4 keV. In the low mass limit where $\beta \rightarrow 1$, we find a 90% UL of $g_{AN}^{eff} \times g_{Ae} < 3.8 \times 10^{-17}$. A comparison of the MAJORANA and EDELWEISS coupling limits is shown in Fig. 4.

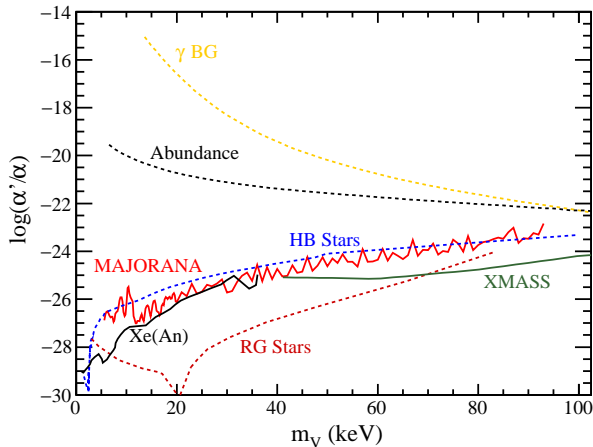


FIG. 3. (Color online) The 90% UL on the vector particle dark matter coupling from the MAJORANA DEMONSTRATOR (red) compared to the astrophysical limits (dashed) from the gamma background (orange), the observed dark matter abundance (black), HB stars (blue), and RG stars (maroon) [11, 42]. Experimental results (solid) from XMASS [39] (green) along with a 2σ limit computed from XENON100 [35] data by H. An, et. al. [43] are also shown. We would like to note that, based on Eqs. 4, 5, and 6, the Xe(An) vector result appears to be inconsistent with the XENON100 pseudoscalar result in Fig. 2.

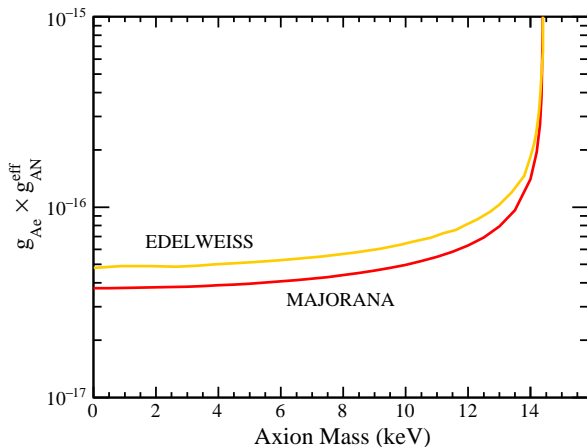


FIG. 4. (Color online) The 90% UL coupling of 14.4-keV solar axions from the MAJORANA DEMONSTRATOR (red) data compared with the limit set by EDELWEISS (orange) [31].

Two non-DM related rare-event searches were carried out using the low energy data and analysis, a Pauli Exclusion violating decay and an electron decay search. While the Pauli Exclusion Principle is a fundamental law of nature, its physical origin is still not fully understood [46–51]. MJD searched for the PEPv transition of an L-shell Ge electron to the K-shell that would manifest as a 10.6 keV [50] shoulder on the K-shell peak. Using the un-

binned likelihood method with a generic signal plus background model, we set a 90% CL on the excess signal rate of 0.03 /kg/d. This equates to a lifetime $\tau > 2.0 \times 10^{31}$ s. Comparing to the 1.7×10^{-16} s lifetime of a standard K_α transition in Ge, one derives an upper limit on the PEPv parameter $\frac{1}{2}\hat{\beta}^2 < 8.5 \times 10^{-48}$, a $\sim 35\%$ improvement over the previous limit [52].

Our data can also be used to set a limit on the decay of the electron to neutrinos. Charge conservation arises from an exact gauge symmetry of quantum electrodynamics with the associated gauge boson being exactly massless. Even so, the possibility of its violation has been theoretically explored [53–59]. The charge-conservation violating process $e^- \rightarrow \nu \bar{\nu}$ would produce an atomic-shell hole. If an electron disappears from the K shell of a Ge atom, resulting atomic emissions will deposit 11.1 keV of energy within the detector. We search for events of this characteristic energy as possible indications of electron decay using a similar analysis as for the PEPv and solar axion search. We determined a lifetime limit of $> 1.2 \times 10^{24}$ y. The best limit on the lifetime for this process is $> 2.4 \times 10^{24}$ y (90% CL) [60].

We found no indication of new physics that would manifest as a peak in the energy spectrum of the data presented in this paper. Upgrades to MJD, detector repairs, and the addition of Module 2 will improve the sensitivity to new physics. Lower background rates in subsequent data sets have already been observed with the installation of the inner electroformed-copper and poly shields. Further research is underway to lower energy thresholds below 5 keV.

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